

SIX DEGREE OF FREEDOM CONTROL OF PLANAR MOTORS

TECHNICAL FIELD

This invention relates generally to electric motors and more particularly to
5 six degree of freedom control of electric planar motors.

BACKGROUND ART

Electric motors are used in a variety of electrical equipment. For example, wafer stages utilize linear or planar electric motors to position a wafer during
10 photolithography and other semiconductor processing.

U.S. Pat. No. 5,623,853, entitled "Precision Motion Stage with Single Guide Beam and Follower Stage" to Novak et al. and U.S. Pat. No. 5,528,118, entitled "Guideless Stage With Isolated Reaction Stage" to Lee ("the '118 patent") discuss examples of semiconductor fabrication equipment and are incorporated herein by reference in their entireties.

U.S. Pat. No. 4,654,571, entitled "Single Plane Orthogonally Moveable Drive System" to Hinds ("the '571 patent") and U.S. Pat. No. 4,535,278, entitled "Two-Dimensional Precise Positioning Device for Use in a Semiconductor Manufacturing Apparatus" to Asakawa ("the '278 patent") discuss two-dimensional planar electric motors. The motors are two-dimensional in that they have two-dimensional arrays of magnets and armatures instead of magnet tracks and one-dimensional armatures. Further, the magnet arrays and two-dimensional armatures may move with respect to each other in more than two dimensions depending upon the design. Conventional two-dimensional linear motors typically have an array of magnets and an armature having one or more coils disposed on one side of the array of magnets.

The '278 patent describes a three degree of freedom planar motor and a control method for independently producing forces in the X, Y and θ_z (rotation about Z) directions. The method described in the '278 patent is better suited for a

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moving-coil electric planar motor. In a moving magnet array electric planar motor, the '278 patent describes a method of controlling the motor that can only produce force with groups of four coils that are fully within the magnetic field of the magnet array. In other words, only coils which are completely covered by the magnet array are used to generate forces and coils which are only partially covered by the magnet array are not used to generate forces. Thus, to provide three degree of freedom control of the planar motor at every position, the magnet array must be sufficiently large to cover an area of at least 5 by 3 coils such that 4 by 2 coils are always completely within the magnetic field of the magnet array at all times.

A platform is attached to the two-dimensional electric motor such that it can be moved and positioned in two or more dimensions by the electric motor. For example, a wafer stage in semiconductor processing equipment may be attached to a coil array or magnet array of a two-dimensional motor and the two-dimensional motor would control the positioning of the wafer stage.

When used to position a platform, conventional two-dimensional electric motors do not smoothly and accurately position the platform. Presently, a coil array in a typical two-dimensional electric motor moves with respect to a stationary magnet array. As exemplified in the '571 patent, cables and hoses are attached to the coil assembly to supply electrical current and coil cooling fluid or air supply to the coils, respectively. However, the hoses and cables impede free motion of the coil assembly.

It is desirable to provide an accurate and efficient method of independently controlling a planar electric motor such that it can be driven to position the platform in six degrees of freedom. It is also be desirable to provide a planar electric motor whose accuracy in positioning is not limited by wiring and/or coil coolant hoses.

SUMMARY OF THE INVENTION

The invention comprises a system and method for independently controlling electric planar motors to move and position in six degrees of freedom. The electric planar motor of the invention is preferably a moving magnet array electric motor comprising a magnet array and a coil array. The current supplied through coils of the coil array interacts with the magnetic field of the magnets of the magnet array to generate forces between the magnet and coil arrays. The generated forces provide motion of the magnet array relative to the coil array in a first, second and third directions generally orthogonal to each other, as well as 5 rotation about the first, second and third directions. The invention teaches the levels of current to be applied to the coils to achieve accurate control of the 10 electric planar motor in six degrees of freedom.

The controlling method of the invention is achieved by the interaction of current in the coil and a magnetic field associated with the magnet. The method for controlling a planar electric motor having a magnetiv array and a coil array for positioning in six degrees of freedom, includes (1) determining the currents to be applied to the coils to generate forces between the magnet array and the coil array in a first (X), second (Y), and third (Z) directions, (2) determining a resultant torque about the first, second, and third directions between the magnet array and the coil array generated by the forces generated by the determined currents; (3) determining current adjustments to compensate for or cancel out the resultant torque; and (4) applying a sum of the determined currents and determined current adjustments to the coils to interact with the magnetic fields of the magnet array.

The method for controlling a planar electric motor for positioning in six degrees of freedom may further include determining the position of the magnet array relative to the coil array and using the determined position to determine currents, resultant torque or current adjustments. The currents to be applied to coils in the portion of the coil array may be selected from sinusoidal, triangular and square waveforms. The method may further include determining the forces to be generated between the magnet array and the coil array in the X, Y, and Z 25 directions to result in forces in the X, Y and Z directions or torques about X, Y, 30 Z.

and Z directions. The current adjustment is preferably determined for each coil in the portion of the coil array.

The invention utilizes all of the coils within the magnetic field of the magnet array, including those which are only partially within the magnetic field of the magnet array. Thus, the currents to be applied to the coils are determined only for coils in the portion of the coil array that is within the magnetic field of the magnetic array, including those coils which are only partially within the magnetic field of the magnet array and the sum of the determined currents and determined current adjustments is applied only to coils in that same portion of the coil array.

The magnet array of the invention covers an area equivalent to at least three four-coil sets or groups or a total of twelve coils. Preferably, the magnet array of the invention covers an area equivalent to at least four four-coil groups for a total of sixteen coils and is preferably square. Thus, the magnetic field of the magnet array of such size interacts with a maximum of twenty-five coils, wholly or partially. In other words, a magnet array of such size covers portions of twenty-five or fewer coils.

In another aspect of the invention, a method for positioning a wafer in a lithography system is provided. The method includes: (1) providing a frame, a stage for supporting the wafer and movable to position the wafer relative to the frame in six degree of freedom, a coil array attached to the frame, and a magnet array adjacent a portion of the coil array, the magnet array being attached to the stage and having magnets generally disposed in a plane, the plane defining a first and second direction; (2) determining currents to be applied to coils in the portion of the coil array to generate forces between the magnet array and the coil array in the first, second, and third directions; (3) determining a resultant torque about the first, second, and third directions between the magnet array and the coil array generated by the forces; (4) determining current adjustments to compensate for the resultant torque; and (5) applying a sum of the currents and current adjustments to the coils to interact with magnetic fields of the magnet array.

5 In another aspect of the present invention, a planar motor is provided. The planar motor includes (1) a first member; (2) a second member that interacts with the first member to generate driving force, the second member being movable relative to the first member in six degrees of freedom including a first, second, and third directions by the driving force; and (3) a controller connected to at least one of the first member and second member, the controller determining information related to resultant torque about the first, second, and third directions between the first member and the second member.

10 The planar electric motor and its control method may also be used in a positioning device. The positioning device has a support member such as a stage, a magnet array, and a coil array. In a moving magnet planar motor, the support member is attached to the moving magnet array and is positionable by the electric motor in six degrees of freedom. Alternatively, the support member is attached to the moving coil array and is positionable by the electric motor in six degrees of freedom.

15 The method appropriately commutes coils and results in accurate and precise movement and positioning of the stage. The methods provide an electrical current distribution or commutation to the active coils of the coil array to control movement of the magnet array with respect to a coil array. The coils of the coil array are distributed in the first (X) and second (Y) direction with a coil period and the magnets of the magnet array are distributed in the first (X) and second (Y) direction with magnet periods of preferably approximately four-thirds the corresponding coil period, though other magnet period to coil period ratios will work.

20 The method applies to both moving magnet and moving coil electric motors although the moving magnet array electric motor is preferred. The moving magnet array electric motor provides more accurate positioning than conventional moving coil electric motors. The moving magnet electric motor does not require wire connections or cooling hoses to the moving part of the motor. Conventional two-dimensional electrical motors are moving coil motors having wires and cooling hoses connected to the moving coil array. By

eliminating wires and hose connections to the moving component, positioning devices using the moving magnet array are more accurate than conventional moving coil platforms. However, although the invention is described in terms of a moving magnet array electric motor, the electric motor may be modified to be a moving coil array electric motor wherein the coil array moves relative to the magnet array.

The method of the invention uses the full active area of the coil array to generate force and torque and permits a large magnet pitch. A large magnet pitch allows the use of larger magnets for a given size motor, which generally have greater magnetic flux. Thus, the use of the full active area of the coil array and a large magnet pitch results in improved motor performance.

The invention's electric motors and positioning devices should be useful in environments requiring precise and wide ranges of positioning. The electric motor and method of the invention is particularly useful in positioning wafers in semiconductor fabrication processes.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1 shows a perspective view of a moving magnet electric motor in accordance with one aspect of the invention;

FIG. 2 shows a perspective view of a magnet array of the moving magnet electric motor of **FIG. 1**;

FIG. 3 shows a perspective view of a coil array of a moving coil electric motor in accordance with another aspect of the invention;

FIG. 4 shows a plan view of a magnet array for use with the coil array of the moving coil electric motor shown in **FIG. 3**;

FIG. 5 is a schematic illustrating a method to achieve force and motion of a portion of a magnet array relative to a portion of a coil array in X and Y directions and rotation about the Z direction in accordance with a method of the invention;

FIG. 6 is a side cross-sectional view of a section of the electric motor of

FIG. 5

FIG. 7 is a schematic of four coil groups illustrating the phases of the coils;

FIG. 8 is a schematic of a group of four coil illustrating the coordinate system of each coil group;

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FIG. 9A depicts a schematic top view of a stage moving over four coil groups illustrating position and force vectors of the coils;

FIG. 9B depicts a schematic top view of the stage covering the coil groups for illustrating a compensation scheme by the partially covered coils;

FIG. 10 is a flow chart of a process to achieve control and motion of a planar motor in six degrees of freedom in accordance with the invention; and

FIG. 11 shows a schematic side view of an example of a photolithography system using the electric motor of the invention.

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DESCRIPTION OF THE INVENTION

The invention comprises a system and method for independently controlling electric planar motors to move and position in six degrees of freedom. The following description is presented to enable any person skilled in the art to make and use the invention. Descriptions of specific applications are provided only as examples. Various modifications to the preferred embodiment will be readily apparent to those skilled in the art, and the general principles defined herein may be applied to other embodiments and applications without departing from the spirit and scope of the invention. Thus, the invention is not intended to be limited to the embodiments shown, but is to be accorded the widest scope consistent with the principles and features disclosed herein.

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FIG. 1 illustrates a moving magnet electric motor (planar motor) 20 in accordance with one aspect of the invention. The electric motor 20 has a coil array 22 and a magnet array 24. Electric current is supplied to the coils 26 of the coil array 22. The current interacts with the magnetic flux of the magnets of the magnet array 24 to generate forces between the coil array 22 and the magnet array 24. The forces move and position the magnet array 24 relative to the coil array

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22. The invention teaches the levels of current to be applied to the coils 26 to achieve six degree of freedom control of the electric motor (planar motor) 20.

As shown in **FIG. 1**, a surface of the coil array 22 is in proximity to an opposing surface of the magnet array 24 during operation of the electric planar motor 20. Preferably, the opposing faces of the coil and magnet arrays 22, 24 are separated by several mm or less during operation. One or more air bearings (not shown) may be provided to separate the coil array 22 from the magnet array 24. Other types of bearings, such as magnetic bearings, may be utilized. Construction and usage of an air bearing are known to those skilled in the art. For example, the '571 patent teaches an air bearing adaptable for use in the invention. The air bearing may position the coil array 22 and the magnet array 24 at a neutral position about which the coil array 22 and the magnet array 24 can move relative to each other in six degrees of freedom.

When one or more air bearings separate the coil array 22 and the magnet array 24 relative to each other, the coil array 22 and/or the magnet array 24 may be potted with any suitable material such as epoxy or may be covered with a flat plate made of, for example, ceramic, composite, or metal, to form generally flat surfaces. The generally flat surfaces improve performance of the air bearing in separating or levitating the coil array 22 and magnet array 24 relative to each other.

Coils 26 of the coil array 22 are periodically distributed in X (first) direction and Y (second) directions. The coil array 22 has a first coil period; 28 in the X direction defined as the distance from the center of one coil to the center of an adjacent coil along the X direction. The coil array 22 further has a second coil period 30 in the Y direction defined as the distance from the center of one coil to the center of an adjacent coil along the Y direction. The coil period 28 in the X direction is preferably approximately equal to the coil period 30 in the Y direction.

As shown in **FIG. 1**, each coil 26 in the coil array 22 has approximately the same shape and size. Although the coils 26 having approximately the same shape and size are preferred, the coils of the coil array 22 may have varying

5 shapes and/or sizes. Each coil 26 preferably covers as much of an area of one coil period in both the X and Y directions as possible in order to maximize the force generated from the interaction between the magnet array 24 and the coil array 26 and thus minimizes the coil power input necessary to achieve a desired amount of force. A rectangular profile of the coil 26 maximizes the area occupied by each coil 26 within the area defined by the coil periods 28, 30 and thus is preferred. As is evident, when the periods 28 and 30 are approximately equal, the profile of the coil 26 approximates a square.

10 Each coil 26 may be disposed about a magnetically impermeable post 32. The magnetically impermeable post 32 facilitates mounting and aligning coil 26 without distorting the magnetic field. In contrast, a magnetically permeable post would focus a magnetic field created by the coil 26 and produce an uneven field distribution over the outline of the coil 26.

15 A backing panel 34 may be attached to one surface or side of the coil array 22. The backing panel 34 may comprise a magnetically permeable material such as iron or may comprise a magnetically impermeable material such as plastic or ceramic. A magnetically permeable backing panel 34 increases the permanent magnetic flux through the coils and thus increases the performance of the electric planar motor 20.

20 As shown in FIG. 1, the coil array 22 has a first coil array dimension 36 in the X direction and a second coil array dimension 38 in the Y direction. Also, the magnet array has a first magnet array dimension 40 in the X direction and a second magnet array dimension 42 in the Y direction. As is evident, the first coil array dimension 36 is larger than the first magnet array dimension 40 and second coil array dimension 38 is larger than the second magnet array dimension 42.

25 FIG. 2 is a perspective view of the magnet array 24, illustrating the surface or side of the magnet array 24 which faces the coil array 22 during operation of the electric motor (planar motor) 20.

30 Similar to the coils of the coil array 22, magnets in the magnet array 24 are also periodically distributed in two directions. The magnet array has a first magnet period 44 in the X direction defined as the distance from the center of one

magnet to the center of the next magnet having the same polarity along the X direction. The magnet array 24 further has a second magnet period 46, in the Y direction, which is the distance from the center of one magnet to the center of the next magnet having the same polarity along the Y direction.

5 The magnet periods 44, 46 of the magnet array 24 in the X and Y directions are related to the periods 28, 30 of the coil array 22 in the X and Y directions, respectively. Specifically, the first magnet period 44 in the X direction is approximately four-thirds of the first coil period 28 in the X direction. Further, the second magnet period 46 in the Y direction is approximately four-thirds of a second coil period 30 in the Y direction. Thus, when the coil periods 10 28, 30 in the X and Y directions are approximately equal, the magnet periods 44, 46 in the X and Y directions are also approximately equal.

15 The magnets are preferably attached to a magnetically permeable backing 48. The magnetically permeable backing 48 completes flux paths between adjacent magnets of opposite polarities to increase the magnetic flux of each polarity, as will be described in more detail below.

20 Preferably, the magnets in the magnet array 24 alternate in polarity in both the X and the Y directions such that the magnets along any diagonals of the X and the Y directions are of the same polarity. The interior magnets 50 in the magnet array 24 preferably have the same magnetic flux. In contrast, non-corner edge magnets 52 and corner magnets 54, 56, 58, 60 of the magnet array 24 have a fraction of the magnetic flux of the interior magnets 50. For example, the non-corner edge magnets 52 of the magnet array 24 have approximately one-half the magnetic flux of the interior magnet 50. The corner magnets 54, 56, 58, 60 have one-quarter the flux of the interior magnets 50. The edge and corner magnets 25 may have any other suitable fractional magnetic fluxes relative to the magnetic fluxes of the interior magnets 50. The fractional fluxes for the non-corner edge magnets 52 and for the corner magnets 54, 56, 58, 60 complete flux paths with each other and with the interior magnets 50 while simultaneously minimizing fringe magnetic fields at the edges of the magnet array 24. Without the fractional 30 magnetic fluxes of the edge and corner magnets, the fringe magnetic fields at the

magnet array edges may otherwise degrade performance of the moving magnet electric motor.

Other types and arrangements of the magnets may also be used in the control method of the invention. For example, wedge magnets may be utilized to facilitate the completion of the magnetic fields. Magnet arrays using wedge magnets are disclosed in, for example, U.S. Patent No. 6,188,147, entitled "Wedge and Transverse Magnet Arrays", issued on February 13, 2001, by Hazelton et al. and copending application Serial No. 09/309,721, entitled "Planar Electric Motor and Positioning Device Having Transverse Magnets", filed on May 11, 1999, both of which are incorporated herein by reference.

The moving magnet planar motor 20 is generally preferable to a moving coil electric motor because the moving magnet array 24 does not require electrical current connections or hoses to carry cooling fluids. Wires and hoses connected to a coil array of the moving coil electric motor may interfere with the motion of the coil array with respect to the magnet array in a moving coil planar motor. Nonetheless, the method of controlling an electric planar motor in six degrees of freedom of the invention as described below may also be applied to a moving coil planar motor, such as shown in FIGS. 3 and 4.

FIGS. 3 and 4 show, respectively, a coil array 122 and a magnet array 124 of a moving coil planar motor 120 according to another aspect of the invention. The coil array 122 is movable relative to the magnet array 124 by supplying electric current to one or more of the coils 126 of the coil array 122. The current interacts with the magnetic flux of the magnets of the magnet array 124 to generate forces between the coil array 122 and the magnet array 124. The forces move and position the coil array 122 relative to the magnet array 124.

A face or side 162 of the coil array 122 is in close proximity to the face or side of the magnet array 124 shown in FIG. 4 during operation of the electric planar motor 120. Preferably, the opposing faces of the coil and magnet arrays 122, 124 are separated by a few mm or less during operation. One or more air bearings 164, as described above with reference to the moving magnet motor 20, may be provided to separate the coil array 122 from the magnet array 124. In

addition, when one or more air bearings 164 separate the coil array 122 and the magnet array 124 relative to each other, the coil array 122 and/or the magnet array 124 may be potted or covered with a flat plate, as described above, to form generally flat surfaces. The generally flat surfaces improve performance of the air bearing in separating or levitating the coil array 122 and magnet array 124 relative to each other.

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Coils 126 of the coil array 122 are periodically distributed in X (first) direction and Y (second) directions. The coil array 122 has a first coil period 128 in the X direction defined as the distance from the center of one coil to the center of an adjacent coil along the X direction. The coil array 122 further has a second coil period 130 in the Y direction defined as the distance from the center of one coil to the center of an adjacent coil along the Y direction. The coil period 128 in the X direction is preferably approximately equal to the coil period 130 in the Y direction.

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Similar to the coils 26 of the coil array 22 of the moving magnet planar motor 20, each coil 126 may be disposed about a magnetically impermeable post 132. Further, a backing panel 134 may be attached to one surface or side of the coil array 122.

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The magnets are preferably attached to a magnetically permeable backing 148. The magnetically permeable backing 148 completes flux paths between adjacent magnets of opposite polarities to increase the magnetic flux of each polarity, as will be described in more detail below.

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As shown in FIG. 4, the magnets in the magnet array 124 are also periodically distributed in the X and Y directions. The magnet array has a first magnet period 144 in the X direction defined as the distance from the center of one magnet to the center of the next magnet having the same polarity along the X direction. The magnet array 124 further has a second magnet period 146 in the Y direction defined as the distance from the center of one magnet to the center of the next magnet having the same polarity along the Y direction.

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Preferably, the magnets in the magnet array 124 alternate in polarity in both the X and the Y directions such that the magnets along any diagonals of the

X and the Y directions are of the same polarity. The first magnet period 144 in the X direction is preferably approximately four-thirds of the first coil period 128 in the X direction. Further, the second magnet period 146 in the Y direction is approximately four-thirds of a second coil period 130 in the Y direction. Thus, when the coil periods 128, 130 in the X and Y directions are approximately equal, the magnet periods 144, 146 in the X and Y directions are also approximately equal.

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In the moving coil planar motor 120, the total number of coils in the coil array 122 is preferably a multiple of 4. As will be described below with reference to **FIG. 5**, the principles of operation for control and movement in six degrees of freedom in the X, Y, and Z directions and rotation about the X, Y, and Z directions use four sets of four adjacent, approximately identically shaped coils.

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The above-described planar motors 20, 120 are similar to those described in U.S. Patent No. 6,208,045 entitled "Electric Motors and Positioning Devices Having Moving Magnet Arrays and Six Degrees of Freedom", issued on March 27, 2001 by Hazelton et al., the entirety of which is incorporated herein by reference.

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Control in Six Degrees of Freedom

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The interactions of currents in the coils and magnetic flux of the magnets in the magnet array to generate forces between the magnet array and the coil array will now be described. Although the following description is in terms of a moving magnet electric motor 20, as is preferred, similar concepts and principles may be used in a moving coil electric motor 120.

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A general qualitative description of the control of the moving magnet motor in three degrees of freedom will be described with reference to **FIG. 5**.

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FIG. 5 is a schematic representation of a section of the moving magnet electric motor 20. The three degrees of freedom are in the X and Y directions and rotation about the Z direction. A general qualitative description of the control of the moving magnet motor in six degrees of freedom will be described with reference to **FIG. 6**. **FIG. 6** is a side cross-sectional view of a portion of the

electric motor section of **FIG. 5**. The six degrees of freedom are in the X, Y, and Z direction and rotation about the X, Y, and Z directions.

FIG. 5 shows a sub-array of the magnet array **24** and a set of four coils **200, 202, 204, 206** which are part of the coil array **22**. In the embodiment shown in **FIG. 5**, each coil has first and second coil periods **28, 30** in the X and Y directions, respectively, approximately equaling three-fourths of first and second magnet periods **44, 46**, respectively.

By appropriately commutating currents flowing in the coils **200, 202, 204, 206**, force is generated between the coil array **22** and the magnet array **24**. For example, in the relative positions of the coil and magnet arrays **22, 24** shown in **FIG. 5**, a counter-clockwise current **208** supplied through coil **200** interacts with the magnetic field of the magnets covered by the coil **200** to exert a force on the coil array **22**, in a positive X direction as indicated by arrow **210**, according to the right-hand rule and the Lorentz force laws.

In a two-phase commutation scheme to generate a force between the coil and magnet arrays **22, 24** in the positive X direction **210**, two coils **200, 202** are commutated. For example, in the relative positions of the coil and magnet arrays **22, 24** shown in **FIG. 5**, the counter-clockwise current **208** supplied through the coil **200** is at a maximum while no current is supplied through the coil **202**. As the coil **200** moves in the positive X direction **210** and its center **200c** approaches the next magnetic pole **212**, the counter-clockwise current **208** supplied through the coil **200** approaches zero. As the coil **200** moves in the positive X direction **210**, the coil **202** also moves in the direction **210**, and its center **202c** moves toward location **214**.

To maintain the force in the positive X direction **210**, a counter-clockwise current is supplied through the coil **202**. The counter-clockwise current in the coil **202** increases sinusoidally to its maximum. When the center **202c** of coil **202** coincides with the location **214**, the current in the coil **202** will be at its maximum.

Similarly, current can be commutated to flow in clockwise direction **216** through the coil **204** to generate a force on the coil array **22** in a negative Y

direction **218**. As in the movement in the positive X direction **210**, the coils **202**, **204** may be commutated in a similar fashion as the coils **200**, **202** to provide a continuous force in the negative Y direction **218**. As with the coils **200**, **202**, the commutation of the coils **202**, **204** is a two phase commutation.

5 With respect to coil **206**, magnets **220**, **222**, **224**, **226** are symmetrically positioned about its center **206c**. When the coil **206** is symmetric about its center **206c** and the coil center **206c** is centrally disposed over the magnets **220**, **222**, **224**, **226**, the forces generated by the interaction between the current through the coil **206** and the magnetic fields of the magnets **220**, **222**, **224**, **226** are cancelled. Thus, unlike the other three coils **200**, **202**, **204**, the coil **206** cannot generate a force between the coil and magnet arrays **22**, **24** in the position as shown in FIG. 5.

10 Only a few examples of commutation have been described. Clearly, as will be appreciated by those skilled in the art, many other commutations may be applied to the coils **200**, **202**, **204**, **206** and the other coils in the coil array **22** to achieve forces and motions in X and Y directions. By providing at least two sets of four coils and by simultaneously generating forces in both the X and Y directions, such as in the positive X and negative Y directions **210** and **218** respectively, the electric motor **20** can also be controlled to rotate the moving magnet array **24** relative to the stationary coil array **22** about the Z direction.

15 Referring now to FIG. 6 the commutation of the coils to generate a force in the Z direction will now be described, enabling six degree of freedom control of the planar motor. By selectively generating forces in the Z direction, torques about the X and Y directions can be achieved.

20 FIG. 6 is a side cross-sectional view of a portion of the electric motor section of FIG. 5 showing the coils **200** and **202** of either a moving coil or moving magnet electric motor. The coil **202** comprises coil portions **202a** and **202b** about its center **202c**. Similarly, coil **200** comprises coil portions **200a** and **200b** about its center **200c**. The coil **202** experiences nonvertical components of magnetic flux density **B** when the magnet is at off-center locations relative to a coil portion, such as coil portions **202a**, **202b**. A current is applied to the coil **202**

which flows through coil portion **202a** in a direction into the plane of **FIG. 6** and through coil portion **202b** in a direction out of the plane of **FIG. 6**. Nonvertical components of the magnetic flux density **B** interact with the current flowing through the coil portions **202a** and **202b** to produce forces F_{202a} and F_{202b} , respectively, in the **Z** direction.

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In a two-phase commutation scheme to exert force on the coil array in the **Z** direction relative to the magnet array, the coils **200** and **202** are commutated. For example, in the position shown in **FIG. 6**, the current through the coil **202** is at a maximum while the coil **200** has no current flowing through it. When the coil **202** is moved in the **X** direction and its coil portion **202a** approaches magnetic pole **228**, the current through the coil **202** will approach zero. As the coil **202** moves in the **X** direction, the coil **200** also moves in the **X** direction and its center portion **200c** moves toward a position directly below magnetic pole **212**.

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To maintain the force in the **Z** direction, the current in the coil **200** is commutated which flows through coil portion **200a** in a direction out of the plane of **FIG. 6** and through coil portion **200b** in a direction into the plane of **FIG. 6**. The current applied to coil **200** will be approximately 90° out of phase relative to the current applied to coil **202**. The current in the coil **200** increases sinusoidally to its maximum. When the center **200c** of coil **200** is directly below magnet pole **212**, the current in the coil **200** will be at its maximum.

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Only a few examples of commutation have been described. Clearly, as will be appreciated by those skilled in the art, many other commutations may be applied to the coils **200**, **202**, **204**, **206** and the other coils in the coil array **22** to achieve force and motion of the coil array **22** with respect to the magnet array **24** in six directions: in the **X**, **Y**, **Z** directions and rotation about the **X**, **Y**, **Z** directions.

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A more detailed quantitative description of the control of the moving magnet motor in six degrees of freedom with torque control will now be described with reference to **FIGS. 7-9**.

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The current commutation scheme is applied to the coils within the magnetic field of the magnets of the magnet array **22**. These are referred to as the

active coils and include coils which are only partially within the magnetic field of the magnets of the magnet array 22. The current supplied through the active coils interact with the magnetic field of the magnet array 24 to generate a force between the magnet and coil arrays 22, 24. No current is applied to the inactive coils, coils that are not within the magnetic field of the magnets of the magnet array 22. Thus, all coils that are wholly or partially within the magnetic field of the magnet array 24 are utilized to generate forces to control the stage in six degrees of freedom.

The utilization of coils only partially within the magnetic field of the magnet array 24 maximizes the forces generated. Further, it allows the utilization of a smaller magnet array 24. Specifically, the magnet array 24 needs to only cover the size of three sets or groups of four coils or a total of twelve coils in order to control the magnet array 24 in six degrees of freedom.

The following derivation of the coil current commutation scheme to control the moving magnet motor 20 in six degrees of freedom is described in terms of a magnet array covering a square of four by four coils. When all four edges of the magnet array or stage are aligned with the edges of the four by four set of coils, the stage completely covers or overlaps with 16 coils. When two of the four edges of the stage are aligned with the edges of the four by four set of coils, the stage completely covers 12 coils and partially covers 8 coils. When none of the four edges of the stage are aligned with the edges of the four by four set of coils, the stage completely covers 9 coils and partially covers 16 coils, for a total of 25 coils. As is evident, in each case, the stage covers an equivalent of 16 full coils.

To achieve six degree of freedom control of the moving magnet motor, the coils need to generate forces in the X, Y, Z directions. As is evident, forces in the X, Y, and Z directions provides linear control and movement in the X, Y, and Z directions. These forces can also generate torques about the X, Y, and Z axes, since there are multiple coils at different X, Y positions. For example, two coils separated in the X direction can produce different amounts of Z force to create a torque about the Y axis.,

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As shown in FIG. 7, the planar motor has four phases **A**, **B**, **C**, and **D** and is essentially a four-phase device. The phase of each coil is defined by the relative positions and polarities of the magnets covered by the coil. The negative sign associated with a given phase indicates that the coil covers similarly positioned magnets with polarities opposite those of the same phase without a negative sign. For example, a **B** phase coil covers the same number and position of magnets as a -**B** phase coil but with opposite polarities.

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To enable six degree of freedom control of the planar motor, moving magnet array or stage must cover an area of twelve coils. Preferably, the area is of sixteen coils, and square of four by four coils. However, other shapes of the magnet array may be utilized, such as a L-shaped, cross-shaped or T-shaped.

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TORQUE CONTROL

In the following derivation of a commutation scheme, the notations of the various parameters are first defined. The torque generated between a single four-coil group and the magnet array is then determined. Finally, the torque generated between the four coil groups and the magnet array or stage is determined. The torque-compensated commutation scheme allows accurate and precise control and positioning of the stage in six degrees of freedom.

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Notation

In the following derivation of the coil current commutation scheme to control the moving magnet motor 20 in six degrees of freedom, various parameters, vectors, and matrices are defined in **Tables I, II, and III**, respectively. Subscripts **A**, **B**, **C**, and **D** denote the four coil phases in a coil group. Subscripts **1**, **2**, **3**, and **4** denote each of the four coil groups under the stage.

TABLE I

Scalar Parameter	Definition
x, y, z	position of the center of gravity of the stage relative to peak-force position
r_x, r_y, r_z	components for the vector r
p_{xi}, p_{yi}, p_{zi}	components of the vector p_i
R_x, R_y, R_z	desired forces for the entire stage in the X, Y and Z directions, respectively
$\Delta_x, \Delta_y, \Delta_z$	magnitude of correction or adjustment factors for X, Y, and Z torque

TABLE II

Vector	No. of Elements	Definition
I	4	currents in each coil of a coil group
r	3	desired force vector for a coil group in the X, Y, and Z directions
f	3	force vector produced by a coil group
t	3	torque vector produced by a coil group, measured at the origin of the coil group
y	6	output force and torque vector produced by a coil group
q_i	3	position vector from the center of gravity of the stage to the origin of coil group i in the X, Y, and Z directions
F	3	force vector produced by the entire stage
T	3	torque vector produced by the entire stage (measured at the center of gravity of the stage)
Y	6	force and torque output vector produced by the entire stage

TABLE III

Matrix	Size	Definition
C	4 x 3	commutation matrix; same for all coil groups
K_f	3 x 4	force constant matrix; same for all coil groups
K_t	3 x 4	torque constant matrix; same for all coil groups
K	6 x 3	input-output matrix for a coil group; same for all coil groups
p	3 x 4	position vectors (each column) for each coil in a group, relative to the origin of the group; same and constant for all coil groups
A	6 x 6	input-output matrix for the complete stage

Force Resulting From Open Loop Commutation for the Coil Group

As shown in FIG. 8, an origin for the four-coil group can be arbitrarily defined as the center of the A-phase (lower-left) coil. A different origin may be selected, preferably at the center of one of the other coils in the coil group. A current vector **I** for the currents in the four coils may be obtained by multiplying a commutation matrix **C**, which depends only on the X-Y position of the stage, by the desired force vector **r**:

$$I = Cr = \begin{bmatrix} \sin(x)\cos(y) & \cos(x)\sin(y) & \cos(x)\cos(y) \\ \cos(x)\cos(y) & -\sin(x)\sin(y) & -\sin(x)\cos(y) \\ -\sin(x)\sin(y) & \cos(x)\cos(y) & -\cos(x)\sin(y) \\ -\cos(x)\sin(y) & -\sin(x)\cos(y) & \sin(x)\sin(y) \end{bmatrix} \begin{bmatrix} r_x \\ r_y \\ r_z \end{bmatrix}$$

The above equation assumes a commutation sinusoidal waveform although other waveforms such as square and/or triangular waveforms, may be utilized.

The force constant for a group of coils is given by:

$$K_f = \begin{bmatrix} \sin(x)\cos(y) & \cos(x)\cos(y) & -\sin(x)\sin(y) & -\cos(x)\sin(y) \\ \cos(x)\sin(y) & -\sin(x)\sin(y) & \cos(x)\cos(y) & -\sin(x)\cos(y) \\ \cos(x)\cos(y) & -\sin(x)\cos(y) & -\cos(x)\sin(y) & \sin(x)\sin(y) \end{bmatrix}$$

Matrix \mathbf{K}_f is simply the transpose of matrix \mathbf{C} , or \mathbf{C}^T . The four columns of matrix \mathbf{K}_f are force-constant vectors for the four coils in the group and the three rows are components corresponding to coordinates X, Y and Z.

The force \mathbf{f} produced by the coil group can be found by multiplying the force-constant matrix \mathbf{K}_f by the current vector \mathbf{I} :

$$\mathbf{f} = \mathbf{K}_f \mathbf{I}$$

After simplification, the equation for force \mathbf{f} is simplified to:

$$\mathbf{f} = \begin{bmatrix} r_x \\ r_y \\ r_z \end{bmatrix} = \mathbf{r}$$

The above result shows that with the commutation law used, a group of four coils can produce any desired force vector. If the commutation waveform were perfectly sinusoidal and the magnets were perfectly symmetrical, there would be no force ripple as the stage moves.

Torque Resulting From Open Loop Commutation for the Coil Group

Torque \mathbf{t} is defined to be about the origin of the coil group. The basic equations for torque \mathbf{t} are given by:

$$\begin{aligned} \mathbf{t} &= \mathbf{p} \times \mathbf{f} \\ \mathbf{t} &= \mathbf{p} \times (\mathbf{K}_f \mathbf{I}) \end{aligned}$$

Factoring out the current \mathbf{I} results in similar equations for the torque constant \mathbf{K}_t :

$$\begin{aligned} \mathbf{K}_t &= \mathbf{t} \mathbf{I}^{-1} \\ \mathbf{K}_t &= \mathbf{p} \times \mathbf{K}_f \end{aligned}$$

A position vector is defined as the vector extending from the origin of the coil group to the center of each coil. Position matrix \mathbf{p} is given by:

$$\mathbf{p} = \begin{bmatrix} 0 & \frac{3\pi}{2} & 0 & \frac{3\pi}{2} \\ 0 & 0 & \frac{3\pi}{2} & \frac{3\pi}{2} \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

The four columns of the \mathbf{p} matrix are the position vectors for the four coils of the coil group.

Matrix \mathbf{K}_t may be determined by taking the cross-products of each column of \mathbf{p} with the respective column of \mathbf{K}_f . This cross-product is:

$$5 \quad \mathbf{K}_t = \frac{3\pi}{2} \begin{bmatrix} 0 & 0 & -\cos(x)\sin(y) & \sin(x)\sin(y) \\ 0 & \sin(x)\cos(y) & 0 & -\sin(x)\sin(y) \\ 0 & -\sin(x)\sin(y) & \sin(x)\sin(y) & \cos(x)\sin(y) - \sin(x)\cos(y) \end{bmatrix}$$

The torque \mathbf{t} produced by the group of coils can be expressed by the following equations:

$$10 \quad \mathbf{t} = \mathbf{K}_t \mathbf{I} = \mathbf{K}_t \mathbf{C} \mathbf{r}$$

$$\mathbf{t} = \frac{3\pi}{2} \begin{bmatrix} 0 & -\sin(y)\cos(y) & \sin^2(y) \\ \sin(x)\cos(x) & 0 & -\sin^2(x) \\ -\sin^2(y) & \sin^2(x) & 0 \end{bmatrix} \begin{bmatrix} r_x \\ r_y \\ r_z \end{bmatrix}$$

Given that the coil group as a whole has three inputs (the three components of the desired force vector) and six outputs (the three components of each of the force and torque vectors), the equations for \mathbf{f} and \mathbf{t} can be rewritten as:

$$15 \quad \begin{bmatrix} f_x \\ f_y \\ f_z \\ t_x \\ t_y \\ t_z \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & -\frac{3\pi}{2}\sin(y)\cos(y) & \frac{3\pi}{2}\sin^2(y) \\ \frac{3\pi}{2}\sin(x)\cos(x) & 0 & -\frac{3\pi}{2}\sin^2(x) \\ -\frac{3\pi}{2}\sin^2(y) & \frac{3\pi}{2}\sin^2(x) & 0 \end{bmatrix} \begin{bmatrix} r_x \\ r_y \\ r_z \end{bmatrix} \quad (1)$$

Denoting the six-element vector containing forces and torques as \mathbf{y} and the six by three matrix \mathbf{K} , the above equation can be rewritten as:

$$\mathbf{y} = \mathbf{K} \mathbf{r}$$

The Complete Stage: Four Four-Coil Groups

FIG. 9A is a schematic of a stage or magnet array **24** moving over four four-coil groups of the coil array **22** illustrating position and force vectors of the coils. The position vectors **q** point from the center of gravity of the stage to the origin of each of the four coil groups.

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As noted above, the stage may cover up to 25 coils, some partially and some completely. The effects of the partially covered coils is simplified in the following analysis. For example, in the lower left coil group **300** shown in **FIG. 9B**, three of the coils are partially covered and one of the coils is completely covered. The three partially covered coils generate only a fraction of the force they would otherwise generate.

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The difference in the force generated is compensated by two partially covered coils **302** above the upper left coil group, two partially covered coils **304** to the right of the lower right coil group, and one partially covered coil **306** in the far upper right corner. Including this effect in the analysis would change the **K** matrices because the moment arms for the partial coils would be different. However, matrix **K** can still be obtained for each coil group as a function of stage position.

The complete stage covers or interacts with an equivalent of four coil groups. Each coil group has an independent set of three inputs (the components of the vector **r**, the desired force vector) and six outputs (the components of **y**, the output force and torque vector). As noted above, subscripts **1**, **2**, **3**, and **4** reference each of the four coil groups under the stage.

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Vector **q_i** is defined as the position vector extending from the center of gravity of the stage to the origin of the coil group **i**. Using this notation, the total force and torque **Y** on the stage can be expressed as:

$$Y = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & -q_{z1} & q_{y1} & 1 & 0 & 0 \\ q_{z1} & 0 & -q_{x1} & 0 & 1 & 0 \\ -q_{y1} & q_{x1} & 0 & 0 & 0 & 1 \end{bmatrix} y_1 + \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & -q_{z2} & q_{y2} & 1 & 0 & 0 \\ q_{z2} & 0 & -q_{x2} & 0 & 1 & 0 \\ -q_{y2} & q_{x2} & 0 & 0 & 0 & 1 \end{bmatrix} y_2 + \dots$$

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Defining each of the six by six matrices \mathbf{Q}_i , the above equation can be rewritten as:

$$\mathbf{Y} = \sum_4 \mathbf{Q}_i \mathbf{y}_i$$

$$\mathbf{Y} = \sum_4 \mathbf{Q}_i \mathbf{K}_i \mathbf{r}_i$$

5 **Table IV** lists the components of the position vector \mathbf{q} and the force vector \mathbf{r} for each coil group.

TABLE IV						
Group	q_x	q_y	q_z	r_x	r_y	r_z
1	$-\frac{5\pi}{2} - x$	$-\frac{5\pi}{2} - y$	-z	R_x	$R_y + \Delta_z$	$R_z + \Delta_x - \Delta_y$
2	$\frac{\pi}{2} - x$	$-\frac{5\pi}{2} - y$	-z	R_x	$R_y - \Delta_z$	$R_z + \Delta_x + \Delta_y$
3	$-\frac{5\pi}{2} - x$	$\frac{\pi}{2} - y$	-z	R_x	$R_y + \Delta_z$	$R_z - \Delta_x - \Delta_y$
4	$\frac{\pi}{2} - x$	$\frac{\pi}{2} - y$	-z	R_x	$R_y - \Delta_z$	$R_z - \Delta_x + \Delta_y$

10 The adjustment factors (Δ 's) are introduced to compensate for the unwanted torque. The following analysis is intended to explain the relationship among the forces, intended torques and the adjustment factors, which comprises a significant part of the invention.

Torque Generated by the Electric Motor on the Stage

15 The total torque generated by all four coil groups can be determined by summing the individual coil group torques and the cross product of the position and force vectors for each coil group. This process is detailed below for each component coordinate X, Y, and Z.

Torque About the X-axis

The total torque about the X-axis is:

$$T_x = \sum t_x + \sum (q_y f_z - q_z f_y) \quad (2)$$

The first term $\sum t_x$ is the X-axis torque about the origin of each coil group.

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Using the values for the force vector \mathbf{r} from **Table IV** in equation (1) above, the torque for each of the four coil groups are expressed as:

$$\begin{aligned} t_{x1} &= \frac{3\pi}{2} \left[-\sin(y) \cos(y) (R_y + \Delta_z) + \sin^2(y) (R_z + \Delta_x - \Delta_y) \right] \\ t_{x2} &= \frac{3\pi}{2} \left[-\sin(y) \cos(y) (R_y - \Delta_z) + \sin^2(y) (R_z + \Delta_x + \Delta_y) \right] \\ t_{x3} &= \frac{3\pi}{2} \left[-\sin(y) \cos(y) (R_y + \Delta_z) + \sin^2(y) (R_z - \Delta_x - \Delta_y) \right] \\ t_{x4} &= \frac{3\pi}{2} \left[-\sin(y) \cos(y) (R_y - \Delta_z) + \sin^2(y) (R_z - \Delta_x + \Delta_y) \right] \end{aligned}$$

Summing these four equations results in the first term $\sum t_x$ of the total torque

equation:

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$$\sum t_x = 4 \frac{3\pi}{2} \left(-\sin(y) \cos(y) R_y + \sin^2(y) R_z \right)$$

Substituting the position vector \mathbf{q} and force vector \mathbf{r} components from **Table IV** into equation (2) results in the following total X-axis torque equation:

$$\begin{aligned} T_x &= \sum t_x + \left(\frac{-5\pi}{2} - y \right) (R_z + \Delta_x - \Delta_y) + z (R_y + \Delta_z) \\ &\quad + \left(\frac{-5\pi}{2} - y \right) (R_z + \Delta_x + \Delta_y) + z (R_y - \Delta_z) \\ &\quad + \left(\frac{\pi}{2} - y \right) (R_z - \Delta_x - \Delta_y) + z (R_y + \Delta_z) \\ &\quad + \left(\frac{\pi}{2} - y \right) (R_z - \Delta_x + \Delta_y) + z (R_y - \Delta_z) \end{aligned}$$

This equation simplifies to:

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$$T_x = 4 \left[\left(-\frac{3\pi}{2} \sin(y) \cos(y) + z \right) R_y + \left(\frac{3\pi}{2} \sin^2(y) - \pi - y \right) R_z - \frac{3\pi}{2} \Delta_x \right]$$

Torque About the Y-axis

Similarly, the torque about the Y-axis can be found from:

$$T_y = \sum t_y + \sum (q_z f_x - q_x f_z) \quad (3)$$

The first term $\sum t_y$ is the Y-axis torque about the origin of each coil group.

5 The Y-axis torque for each coil group can be expressed by:

$$\begin{aligned} t_{y1} &= \frac{3\pi}{2} [\sin(x) \cos(x) (R_x) - \sin^2(x) (R_z + \Delta_x - \Delta_y)] \\ t_{y2} &= \frac{3\pi}{2} [\sin(x) \cos(x) (R_x) - \sin^2(x) (R_z + \Delta_x + \Delta_y)] \\ t_{y3} &= \frac{3\pi}{2} [\sin(x) \cos(x) (R_x) - \sin^2(x) (R_z - \Delta_x - \Delta_y)] \\ t_{y4} &= \frac{3\pi}{2} [\sin(x) \cos(x) (R_x) - \sin^2(x) (R_z - \Delta_x + \Delta_y)] \end{aligned}$$

Summing these four equations results in the first term $\sum t_y$ of the total torque equation:

$$\sum t_y = 4 \frac{3\pi}{2} (\sin(x) \cos(x) R_x - \sin^2(x) R_z)$$

10 Substituting the position vector q and force vector r components from

Table IV into equation (3) results in the following total Y-axis torque equation:

$$\begin{aligned} T_y &= \sum t_y - zR_x + \left(\frac{5\pi}{2} + x \right) (R_z + \Delta_x - \Delta_y) \\ &\quad - zR_x + \left(\frac{-\pi}{2} + x \right) (R_z + \Delta_x + \Delta_y) \\ &\quad - zR_x + \left(\frac{5\pi}{2} + x \right) (R_z - \Delta_x - \Delta_y) \\ &\quad - zR_x + \left(\frac{-\pi}{2} + x \right) (R_z - \Delta_x + \Delta_y) \end{aligned}$$

This equation simplifies to:

$$T_y = 4 \left[\left(\frac{3\pi}{2} \sin(x) \cos(x) - z \right) R_x + \left(\frac{-3\pi}{2} \sin^2(x) + \pi + x \right) R_z - \frac{3\pi}{2} \Delta_y \right]$$

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Torque About the Z-axis

Similarly, the torque about the Z-axis can be found from:

$$T_z = \sum t_z + \sum (q_x f_y - q_y f_x) \quad (4)$$

The first term $\sum t_z$ is the Z-axis torque about the origin of each coil group.

The Z-axis torque for each coil group can be expressed by:

$$\begin{aligned} t_{z1} &= \frac{3\pi}{2} [-\sin^2(y)R_x + \sin^2(x)(R_y + \Delta_z)] \\ t_{z2} &= \frac{3\pi}{2} [-\sin^2(y)R_x + \sin^2(x)(R_y - \Delta_z)] \\ t_{z3} &= \frac{3\pi}{2} [-\sin^2(y)R_x + \sin^2(x)(R_y + \Delta_z)] \\ t_{z4} &= \frac{3\pi}{2} [-\sin^2(y)R_x + \sin^2(x)(R_y - \Delta_z)] \end{aligned}$$

5 Summing these four equations results in the first term $\sum t_z$ of the total torque equation:

$$\sum t_z = 4 \frac{3\pi}{2} (-\sin^2(y)R_x + \sin^2(x)R_y)$$

Substituting the position vector q and force vector r components from Table IV into equation (4) results in the following total Z-axis torque equation:

$$\begin{aligned} T_z &= \sum t_z + \left(\frac{-5\pi}{2} - x \right) (R_y + \Delta_z) + \left(\frac{5\pi}{2} + y \right) R_x \\ &\quad + \left(\frac{\pi}{2} - x \right) (R_y - \Delta_z) + \left(\frac{5\pi}{2} + y \right) R_x \\ &\quad + \left(\frac{-5\pi}{2} - x \right) (R_y + \Delta_z) + \left(\frac{-\pi}{2} + y \right) R_x \\ &\quad + \left(\frac{\pi}{2} - x \right) (R_y - \Delta_z) + \left(\frac{-\pi}{2} + y \right) R_x \end{aligned}$$

10 This equation simplifies to:

$$T_z = 4 \left[\left(\frac{-3\pi}{2} \sin^2(y) + \pi + y \right) R_x + \left(\frac{3\pi}{2} \sin^2(x) - \pi - x \right) R_y - \frac{3\pi}{2} \Delta_z \right]$$

Input-Output Matrix for the Stage

15 Combining the three equations for total torque T_x , T_y , and T_z with the total force F_x , F_y , and F_z produced by the stage gives the following equation that represents the input-output behavior of the entire stage:

$$\begin{bmatrix} F_x \\ F_y \\ F_z \\ T_x \\ T_y \\ T_z \end{bmatrix} = 4 \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & \frac{-3\pi}{2} \sin(y) \cos(y) + z & \begin{pmatrix} \frac{3\pi}{2} \sin^2(y) \\ -\pi - y \end{pmatrix} & \frac{-3\pi}{2} & 0 & 0 \\ \frac{3\pi}{2} \sin(x) \cos(x) - z & 0 & \begin{pmatrix} \frac{-3\pi}{2} \sin^2(x) \\ +\pi + x \end{pmatrix} & 0 & \frac{-3\pi}{2} & 0 \\ \begin{pmatrix} \frac{-3\pi}{2} \sin^2(y) \\ +\pi + y \end{pmatrix} & \begin{pmatrix} \frac{3\pi}{2} \sin^2(x) \\ -\pi - x \end{pmatrix} & 0 & 0 & 0 & \frac{-3\pi}{2} \end{bmatrix} \begin{bmatrix} R_x \\ R_y \\ R_z \\ \Delta_x \\ \Delta_y \\ \Delta_z \end{bmatrix}$$

The equation can be rewritten as:

$$\mathbf{Y} = \mathbf{AU}$$

Matrix **A** is:

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$$\mathbf{A} = \begin{bmatrix} 4 & 0 & 0 & 0 & 0 & 0 \\ 0 & 4 & 0 & 0 & 0 & 0 \\ 0 & 0 & 4 & 0 & 0 & 0 \\ \times & \times & \times & -6\pi & 0 & 0 \\ \times & \times & \times & 0 & -6\pi & 0 \\ \times & \times & \times & 0 & 0 & -6\pi \end{bmatrix}$$

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The "x" terms of matrix **A** are terms that depend only on the stage position. The total force produced by the stage depends only on the desired force vector (R_x, R_y, R_z). Although the force vector affects the torque generated, the correction terms $\Delta_x, \Delta_y, \Delta_z$ can be used to generate desired and/or predetermined torques.

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Torque Compensation

The method of the invention for independently controlling the forces and

torque generated by the electric motor in six degrees of freedom preferably

includes determining the uncompensated torque about the X, Y, and Z axis

generated from the commutation scheme using the desired force vector **R** and then

determining the correction terms $\Delta_x, \Delta_y, \Delta_z$ that make the total torque equal the

desired value. The uncompensated torque about the X, Y, and Z axis generated

from the commutation scheme may be determined using force vector terms R_x , R_y , R_z and the lower-left nine elements of matrix A . The correction terms Δ_x , Δ_y , Δ_z may be determined by dividing the desired torque minus the uncompensated torque about the X, Y, and Z axis by 6π . The torque-compensated commutation equations thus uses the terms R_x , R_y , R_z , Δ_x , Δ_y , and Δ_z .

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FIG. 10 is a flow chart illustrating the process or method 250 of achieving motion of the magnet array 24 with respect to the coil array 22. The method or process 250 begins at a start procedure 252. Procedure 254 positions the magnet array 24 relative to the coil array 22. Procedure 256 determines the position of the magnet array 24 relative to the coil array 22 with the use of a measurement device such as an interferometer. Procedure 258 energizes the active coils of the coil array 22 according to the commutation scheme as determined with the method described above. Procedure 260 determines whether a stop condition exists. If not, the method 250 returns to procedure 256 to determine the position of the magnet array 24 relative to the coil array 22. If it is time to stop the motor, the method 250 terminates at a procedure 262.

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Procedure 258 controls the relative forces between a portion of the coil array and the moving magnet array by selectively applying predetermined currents to the appropriate coils such that the appropriate coils interact with the magnetic fields associated with the magnets in the magnet array and generate Lorentz forces.

As noted, the above-described method of independently controlling a moving magnet planar electric motor to position the platform in six degrees of freedom may be utilized with a moving coil electric motor. However, the 30
commutation scheme is simpler because all the coils of the moving coil array are within the magnet field of the magnet array and no coils are partially within the magnet field. Thus, the forces generated between the coil and magnet arrays act through the center of the coils given that the coils are always in the same position relative to the center of gravity of the moving coil array or stage. Therefore, torque control is straightforward in a moving coil planar electric motor.

The electric motors of the invention may be used with a lithography system such as shown and described in, for example, the '118 patent referenced above. **FIG. 11** shows a schematic side view of an example of a photolithography system **800** using the electric motor **812** of the invention. Although the photolithography system **800** is described as utilizing a moving magnet electric motor **812**, the photolithography system may be adapted to utilize a moving coil electric motor or other variations of the moving magnet electric motor.

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The photolithography system (exposure apparatus) **800** generally comprises an illumination system **802** (irradiation apparatus), a first frame **834**, a reticle stage assembly **810**, a second frame **832**, the optical assembly (lens assembly) **804**, a third frame **826**, and a wafer stage assembly **820**. A moving magnet electric motor **812** provided herein can be used as a part of the wafer stage assembly **820**. Alternately, with the disclosure provided herein, the moving magnet electric motor **812** can be modified for use as a part of the reticle stage assembly **810**.

The lithography system **800** is particularly useful as a lithographic device that transfers a pattern (not shown) of an integrated circuit from a reticle **806** onto a substrate such as a semiconductor wafer **808**. The lithography system **800** mounts to the mounting base **850**, e.g., the ground, a base, or floor or some other supporting structure.

The first frame **834** supports the illumination system **802** above the mounting base **850**. The second frame **832** supports the reticle stage assembly **810** above the mounting base **850**. The third frame **826** supports the optical assembly **804** above the mounting base **850**. The frames **834**, **832**, and **826** are coupled to the mounting base **850** by vibration damping devices **860**. The design of these frames **834**, **832**, and **826** can be varied to suit the design requirements for the rest of the lithography system **800**.

The illumination system includes an illumination source **851** and an illumination optical assembly **852**. The illumination source **851** emits a beam (irradiation) of light energy. The illumination optical assembly **852** guides the beam of light energy from the illumination source **851** to the optical assembly

804. The beam illuminates selectively different portions of the reticle 806 and exposes the wafer 808. In Figure 8, the illumination system 802 is illustrated as being supported above the reticle stage assembly 810. However, the illumination system 802 is secured to one of the sides of the frames and the energy beam from the illumination source 851 is directed to above the reticle stage assembly 810 with the illumination optical assembly 852.

5 The optical assembly 804 projects and/or focuses the light passing through the reticle 806 to the wafer 808. Depending upon the design of the lithography system 800, the optical assembly 804 can magnify or reduce the image 10 illuminated on the reticle 806.

10 The reticle stage assembly 810 holds and positions the reticle 806 relative to the optical assembly 804 and the wafer 808. Similarly, the wafer stage assembly 820 holds and positions the wafer 808 with respect to the projected image of the illuminated portions of the reticle 806 in the operation area. In 15 Figure 8, the wafer stage assembly 820 utilizes the moving magnet electric motor 812 having features of the present invention. Depending upon the design, the lithography system 800 can also include additional wafer stage assemblies 820 to increase the throughput of the lithography system 800.

20 The wafer 808 is held by vacuum suction on a wafer holder 849 that is supported on the wafer stage assembly 820. The wafer stage assembly 820 is structured so that it can be moved in several (e.g., three to six) degrees of freedom by a planar motor (the moving magnet electric motor 812) under precision control by a wafer stage driver 853 and system controller 855, to position the wafer 808 at a desired position and orientation, and to move the wafer 808 relative to the 25 projected image of the illuminated portions of the reticle 806 in the operation area. The moving magnet electric motor 812 comprises a moving magnet array 814 and a fixed coil array 818. The moving magnet array 814 is connected to the wafer holder 849 and supported by air bearings 816 on a plate 836. The plate 836 is positioned between the moving magnet array 814 and the fixed coil array 818 and connected to the third frame 826. The plate 826 may be made of non- 30 magnetic materials, for example, carbon fiber plastics, ceramics such as Zerodur

ceramics, Al_2O_3 ceramics, and like materials that do not impair the magnetic flux generated by the magnet array 814. The plate 836 may be formed with a thick honeycomb structure or other types of reinforced structure to prevent it from bending. The coil array 818 is attached to the backing panel 822. The backing panel 822 is rigidly supported on the mounting base 850 on support 861.

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However, the baking panel 822 may be supported on the mounting base 850 by the vibration damping device 860 same as the frames 834, 832, and 826.

The lithography system 800 includes a first measuring system that detects the position of the wafer holder 849 (wafer 808) relative to the optical assembly 804 as a reference structure at least along the X, Y axis and about the Z (theta Z) axis. This information corresponds to the position of the magnet array 814 relative to the coil array 818. The first measuring system can utilize an interferometer system. In this embodiment, the first measuring system comprises a first interferometer block 856 supported on the third frame 826 and a first moving mirror 857 attached to the wafer holder 849. The first interferometer block 856 generates a pair of spaced apart laser beams (not shown) to the first moving mirror 857 and detects the beams reflected from the first moving mirror 857 to output the information of the position of the wafer 808 to the system controller 855. Further, the lithography system 800 includes a second measuring system that detects the position of the reticle stage assembly 810 (reticle 806) relative to the optical assembly 804 as a reference structure at least along the X, Y axis and about the Z (theta Z) axis. Somewhat similarly, the second measuring system comprises a second interferometer block 858 supported on the third frame 826 and a second moving mirror 859 attached to the reticle stage assembly 810.

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20 The second interferometer block 858 generates a pair of spaced apart laser beam (not shown) to the second moving mirror 859 and detects the beams reflected from the second moving mirror 859 to output the information of the position of the reticle 806 to the system controller 855.

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30 The system controller 855 is connected to the first interferometer block 856, the second interferometer block 858, the wafer stage driver 853, and a reticle stage driver 854. The system controller 855 controls each of drivers 854 and 853

for the reticle stage assembly 810 and wafer stage assembly 820 based on the information of the positions outputted from the interferometer blocks 856 and 858 and the desired position of the reticle and the wafer stage assemblies. In this embodiment, the system controller 855 determines current to be applied to coils included in the coil array 818 of the electric motor 812, and outputs this information to the wafer stage driver 853. The wafer stage driver 853 is connected to each coil of the coil array 818 and drives the electric motor 812 in accordance with the information. Further, the system controller 855 determines a resultant torque between the magnet array 814 and the coil array 818 and the correction current to compensate for the resultant torque as mentioned above. The wafer stage driver 853 drives the electric motor 812 based on this information. As a result, the wafer 808 is positioned precisely in wide ranges.

The electric motor 812 can be structured as the moving coil planar motor such as shown in FIGS. 3 and 4.

There are a number of different types of photolithographic devices. For example, photography system 800 can be used as a scanning type photolithography system which exposes the pattern from reticle 806 onto wafer 808 with reticle 806 and wafer 808 moving synchronously. In a scanning type lithographic device, reticle 806 is moved perpendicular to an optical axis of lens assembly 804 by reticle stage assembly 810 and wafer 808 is moved perpendicular to an optical axis of lens assembly 804 by wafer stage assembly 820. Scanning of reticle 806 and wafer 808 occurs while reticle 806 and wafer 808 are moving synchronously.

Alternately, photolithography system 800 can be a step-and-repeat type photolithography system that exposes reticle 806 while reticle 806 and wafer 808 are stationary. In the step and repeat process, wafer 808 is in a constant position relative to reticle 806 and lens assembly 804 during the exposure of an individual field. Subsequently, between consecutive exposure steps, wafer 808 is consecutively moved by wafer stage assembly 820 perpendicular to the optical axis of lens assembly 804 so that the next field of semiconductor wafer 808 is brought into position relative to lens assembly 804 and reticle 806.

However, the use of photolithography system 800 provided herein is not limited to a photolithography system for a semiconductor manufacturing. Photolithography system 800, for example, can be used as an LCD photolithography system that exposes a liquid crystal display device pattern onto a rectangular glass plate or a photolithography system for manufacturing a thin film magnetic head. Further, the present invention can also be applied to a proximity photolithography system that exposes a mask pattern by closely locating a mask and a substrate without the use of a lens assembly. Additionally, the present invention provided herein can be used in other devices, including other semiconductor processing equipment, machine tools, metal cutting machines, and inspection machines.

The illumination source 851 can be g-line (436 nm), i-line (365 nm), KrF excimer laser (248 nm), ArF excimer laser (193 nm) and F₂ laser (157 nm). Alternatively, illumination source 851 can also use charged particle beams such as x-ray and electron beam. For instance, in the case where an electron beam is used, thermionic emission type lanthanum hexaboride (LaB₆) or tantalum (Ta) can be used as an electron gun. Furthermore, in the case where an electron beam is used, the structure could be such that either a mask is used or a pattern can be directly formed on a substrate without the use of a mask.

With respect to lens assembly 804, when far ultra-violet rays such as the excimer laser is used, glass materials such as quartz and fluorite that transmit far ultra-violet rays is preferably used. When the F₂ type laser or x-ray is used, lens assembly 804 should preferably be either catadioptric or refractive (a reticle should also preferably be a reflective type), and when an electron beam is used, electron optics should preferably comprise electron lenses and deflectors. The optical path for the electron beams should be in a vacuum.

Also, with an exposure device that employs vacuum ultra-violet radiation (VUV) of wavelength 200 nm or lower, use of the catadioptric type optical system can be considered. Examples of the catadioptric type of optical system include the disclosure Japan Patent Application Disclosure No. 8-171054 published in the Official Gazette for Laid -Open Patent Applications and its counterpart U.S.

5 Patent No. 5,668,672, as well as Japan Patent Application Disclosure No. 10-20195 and its counterpart U.S. Patent No. 5,835,275. In these cases, the reflecting optical device can be a catadioptric optical system incorporating a beam splitter and concave mirror. Japan Patent Application Disclosure No. 8-334695 published in the Official Gazette for Laid-Open Patent Applications and its counterpart U.S. Patent No. 5,689,377 as well as Japan Patent Application Disclosure No. 10-3039 and its counterpart U.S. Patent No. 873,606 (Application Date: 6-12-97) also use a reflecting-refracting type of optical system incorporating a concave mirror, etc., but without a beam splitter, and can also be employed with this invention. The 10 disclosures in the above-mentioned U.S. patents, as well as the Japan patent applications published in the Official Gazette for Laid-Open Patent Applications are incorporated herein by reference.

15 Further, in photolithography systems, when linear motors (see U.S. Patent Nos. 5,623,853 or 5,528,118) are used in a wafer stage or a reticle stage, the linear motors can be either an air levitation type employing air bearings or a magnetic levitation type using Lorentz force or reactance force. Additionally, the stage could move along a guide, or it could be a guideless type stage which uses no 20 guide. The disclosures in U.S. Patent No. 5,523,853 and 5,528,118 are incorporated herein by reference.

25 Alternately, one of the stages could be driven by a planar motor, which drives the stage by electromagnetic force generated by a magnet unit having two-dimensionally arranged magnets and an armature coil unit having two-dimensionally arranged coils in facing positions. With this type of driving system, either one of the magnet unit or the armature coil unit is connected to the stage and the other unit is mounted on the moving plane side of the stage.

30 Movement of the stages as described above generates reaction forces which can affect performance of the photolithography system. Reaction forces generated by the wafer (substrate) stage motion can be mechanically released to the floor (ground) by use of a frame member as described in U.S. Patent No. 5,528,118 and published Japanese Patent Application Disclosure No. 8-166475. Additionally, reaction forces generated by the reticle (mask) stage motion can be

mechanically released to the floor (ground) by use of a frame member as described in U.S. Patent No. 5,874,820 and published Japanese Patent Application Disclosure No. 8-330224. The disclosures in U.S. Patent Nos. 5,528,118 and 5,874,820 and Japanese Patent Application Disclosure No. 8-330224 are incorporated herein by reference.

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As described above, a photolithography system according to the above described embodiments can be built by assembling various subsystems, including each element listed in the appended claims, in such a manner that prescribed mechanical accuracy, electrical accuracy and optical accuracy are maintained. In order to maintain the various accuracies, prior to and following assembly, every optical system is adjusted to achieve its optical accuracy. Similarly, every 10 mechanical system and every electrical system are adjusted to achieve their respective mechanical and electrical accuracies. The process of assembling each subsystem into a photolithography system includes mechanical interfaces, electrical circuit wiring connections and air pressure plumbing connections 15 between each subsystem. Needless to say, there is also a process where each subsystem is assembled prior to assembling a photolithography system from the various subsystems, total adjustment is performed to make sure that every 20 accuracy is maintained in the complete photolithography system. Additionally, it is desirable to manufacture an exposure system in a clean room where the temperature and humidity are controlled.

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Further, semiconductor devices can be fabricated using the above described systems, by the process shown generally in **FIG. 12**. In step **401** the device's function and performance characteristics are designed. Next, in step **402**, a mask (reticle) having a pattern is designed according to the previous designing step, and in a parallel step **403**, a wafer is made from a silicon material. The mask pattern designed in step **402** is exposed onto the wafer from step **403** in step **404** by a photolithography system described hereinabove consistent with the principles of the present invention. In step **405** the semiconductor device is assembled (including the dicing process, bonding process and packaging process), then finally the device is inspected in step **406**.

5 **FIG. 13** illustrates a detailed flowchart example of the above-mentioned step 404 in the case of fabricating semiconductor devices. In step 411 (oxidation step), the wafer surface is oxidized. In step 412 (CVD step), an insulation film is formed on the wafer surface. In step 413 (electrode formation step), electrodes are formed on the wafer by vapor deposition. In step 414 (ion implantation step), ions are implanted in the wafer. The above mentioned steps 411-414 form the preprocessing steps for wafers during wafer processing, and selection is made at each step according to processing requirements.

10 At each stage of wafer processing, when the above-mentioned preprocessing steps have been completed, the following post-processing steps are implemented. During post-processing, initially, in step 415 (photoresist formation step), photoresist is applied to a wafer. Next, in step 416, (exposure step), the above-mentioned exposure device is used to transfer the circuit pattern of a mask (reticle) to a wafer. Then, in step 417, (developing step), the exposed wafer is developed, and in step 418 (etching step), parts other than residual photoresist (exposed material surface) are removed by etching. In step 419 (photoresist removal step), unnecessary photoresist remaining after etching is removed.

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20 Multiple circuit patterns are formed by repetition of these preprocessing and post-processing steps.

25 It will be apparent to those skilled in the art that various modifications and variations can be made in the methods described, in the stage device, the control system, the material chosen for the present invention, and in construction of the photolithography systems as well as other aspects of the invention without departing from the scope or spirit of the invention.

30 Although only a few exemplary embodiments of this invention have been described in detail above, those skilled in the art will readily appreciate that many modifications are possible in the exemplary embodiments without materially departing from the novel teachings and advantages of this invention. For example, although depicted as being planar, the arrays of magnetic poles and coils can have either constant or varying curvature in one or two-dimensions as in cylindrical, toroidal, and spherical arrangements of magnetic poles and coils. For

cylindrical arrangements, latitudinal and longitudinal directions may be defined, for example, in standard cylindrical coordinates with corresponding diagonal directions, and parallel arrays and coils lie on parallel surfaces. Accordingly, all such modifications are intended to be within the scope of the following claims.

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